Near Term* Plans for the Fermilab Proton Source

Eric Prebys
FNAL Accelerator Division

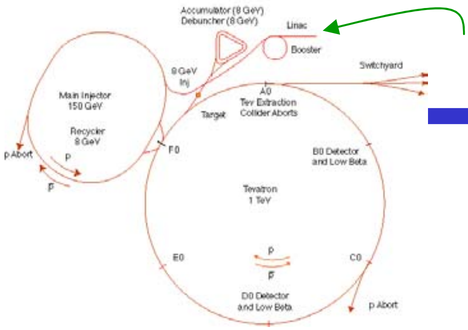
*Near term = "prior to proton driver"

Outline

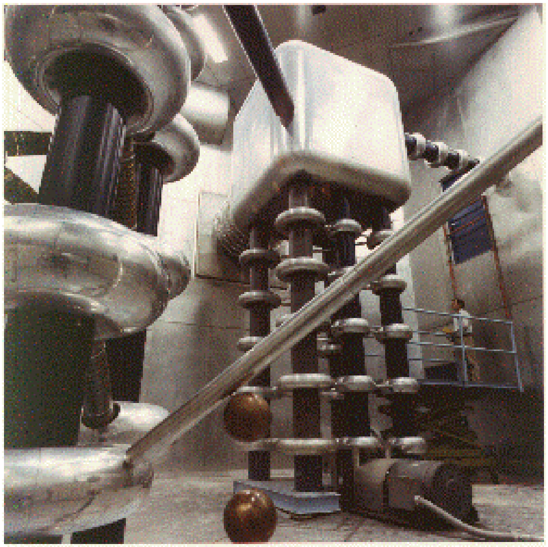
- Finley Report
- Background
  - Linac
  - Booster
  - Main Injector
  - Proton Limitations
- Projected Proton Demands
  - Experimental Requests
  - Proton Economics
- Operational Issues and Current Performance
- Recent Improvements
- The Plan
  - The process
  - Near term
  - Issues for the next year
  - Longer term decisions

Proton Team ("Finley Report")

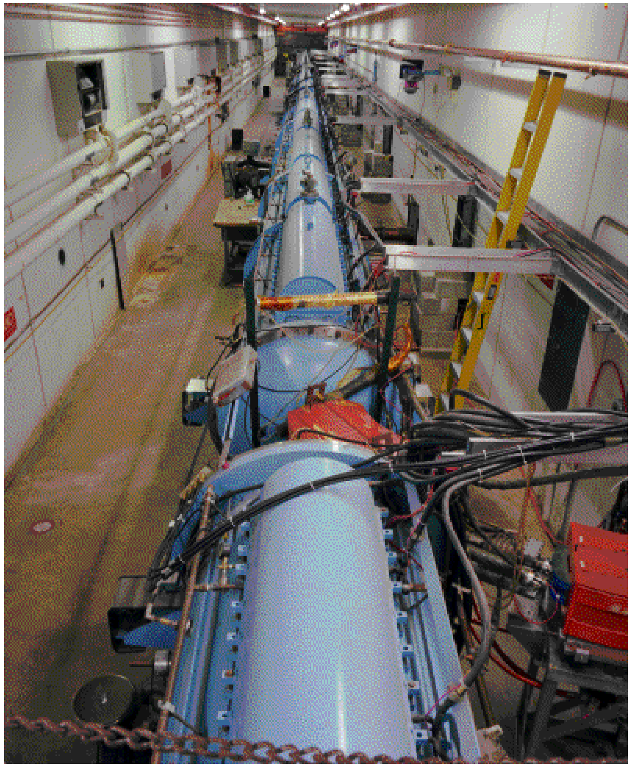
- Group formed in early 2003 to study proton demands and needs for the "near" future (through ~2012 or so), in the absence of a proton driver.
- Work culminated in a report to the director, available at www.fnal.gov/directorate/program_planning/studies/ProtonReport.pdf
- This work will form the basis of "The Proton Plan".
- No big surprises [see P. Kasper "Getting Protons to NuMI (It's a worry)", 2001].



Preac(cellerator) and Linac

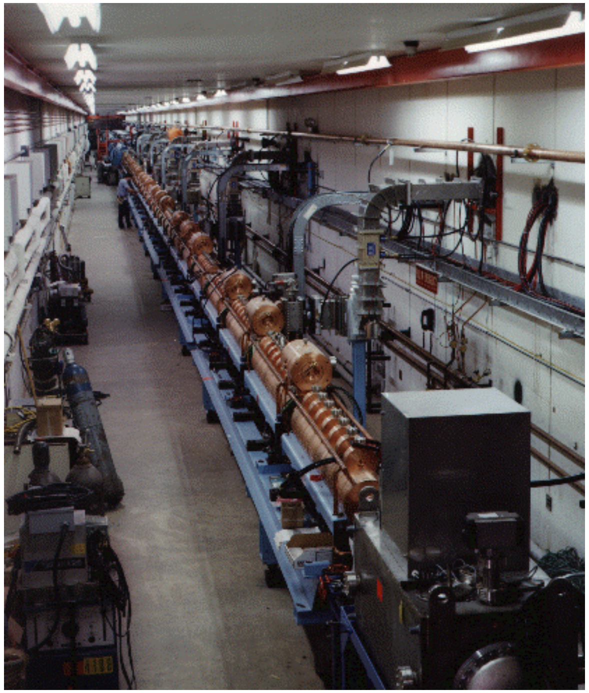


"Preac" - Static Cockroft-Walton generator accelerates H- ions from 0 to 750 KeV.



"Old linac"- 200 MHz "Alvarez tubes" accelerate H- ions from 750 keV to 116 MeV

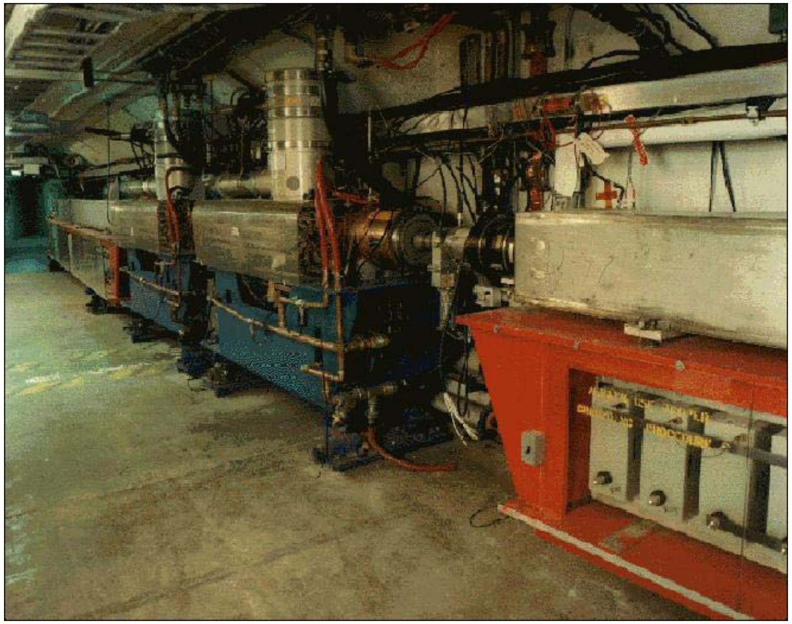
"New linac"- 800 MHz "π cavities" accelerate H- ions from 116 MeV to 400 MeV



Preac/Linac can deliver about 45 mA of current for about 40 usec at a 15 Hz repetition rate (not a bottleneck)

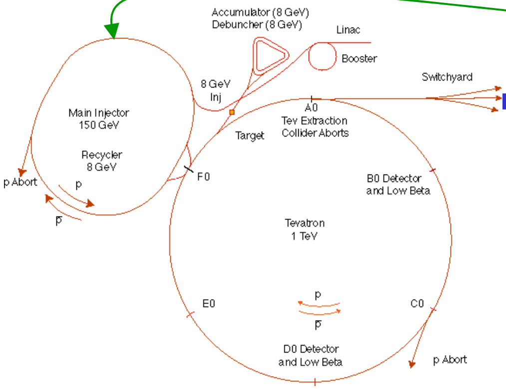
Booster

- 400 MeV Linac H- beam is injected into booster.
- The lattice magnets in the Booster form a 15 Hz resonant circuit, setting the instantaneous cycle rate, but ramped elements limit the average repetition rate to somewhat lower.
- From the Booster, beam can be directed to
  - The Main Injector
  - MiniBooNE
  - The Radiation Damage Facility (RDF)
  - A dump.



- The 15 Hz cycle sets a fundamental clock rate for the entire complex.
- One full booster "batch" sets a fundamental unit of protons throughout the accelerator complex (max 5E12).

Main Injector



- The Main Injector can accept 8 GeV protons OR antiprotons from
  - Booster
  - The anti-proton accumulator
  - The Recycler (which shares the same tunnel)
- It can accelerate protons to 120 GeV (in a minimum of 1.4 s) and deliver them to
  - The antiproton production target.
  - The fixed target area.
  - (soon) The NUMI beamline.
- It can accelerate protons OR antiprotons to 150 GeV and inject them into the Tevatron.

- The Main Injector holds six booster batches, in the absence of exotic loading schemes (slip stacking, RF barrier, etc).
- It's envisioned that two slipstacked batches will be used for stacking and the rest for NUMI and/or switchyard 120.

What Limits Total Proton Intensity?

- Maximum number of Protons the Booster can stably accelerate: 5E12
- Maximum average Booster rep. Rate: currently 7.5 Hz, may have to go to 10 Hz for NuMI+ *(full)* MiniBooNE
- (NUMI only) Maximum number of booster batches the Main Injector can hold: currently 6 *in principle*, possibly go to 11 with fancy loading schemes in the future
- (NUMI only) Minimum Main Injector ramp cycle time (NUMI only): 1.4s+loading time (at least 1/15s**nbatches*)
- Losses in the Booster:
  - Above ground radiation
  - Damage and/or activation of tunnel components

Our biggest worry at the moment!!!!

Fermilab Program

Interest in Continuing MiniBooNE (or other 8 GeV line exp.)

Program	Facility	2003	2004	2005	2006	2007
Tevatron Collider	C0					BTeV
	B0 & D0	CDF & Dzero	CDF & Dzero	CDF & Dzero	CDF & Dzero	CDF & Dzero
Neutrino Program	Booster	MiniBooNE	MiniBooNE	M B Open	Open	Open
	FMI			MINOS	MINOS	MINOS
Meson 120	MT	Test Beam	Test Beam	Test Beam	Test Beam	Test Beam
	MC	E907/MIPP	E907/MIPP	E907/MIPP	Open	Open

Program	Facility	2008	2009	2010	2011	2012
Tevatron Collider	C0	BTeV	BTeV	BTeV	BTeV	BTeV
	B0 & D0	CDF & Dzero	CDF & Dzero	Open	Open	Open
Neutrino Program	Booster	Open	Open	Open	Open	Open
	FMI	MINOS	MINOS	Open	Open	Open
Meson 120	MT	Test Beam	Test Beam	Test Beam	Test Beam	Test Beam
	MC	E906	E906-Drell Yan	E906-Drell Yan	E906-Drell Yan	Open
	ME/MP	Open	CKM	CKM	CKM	CKM Open

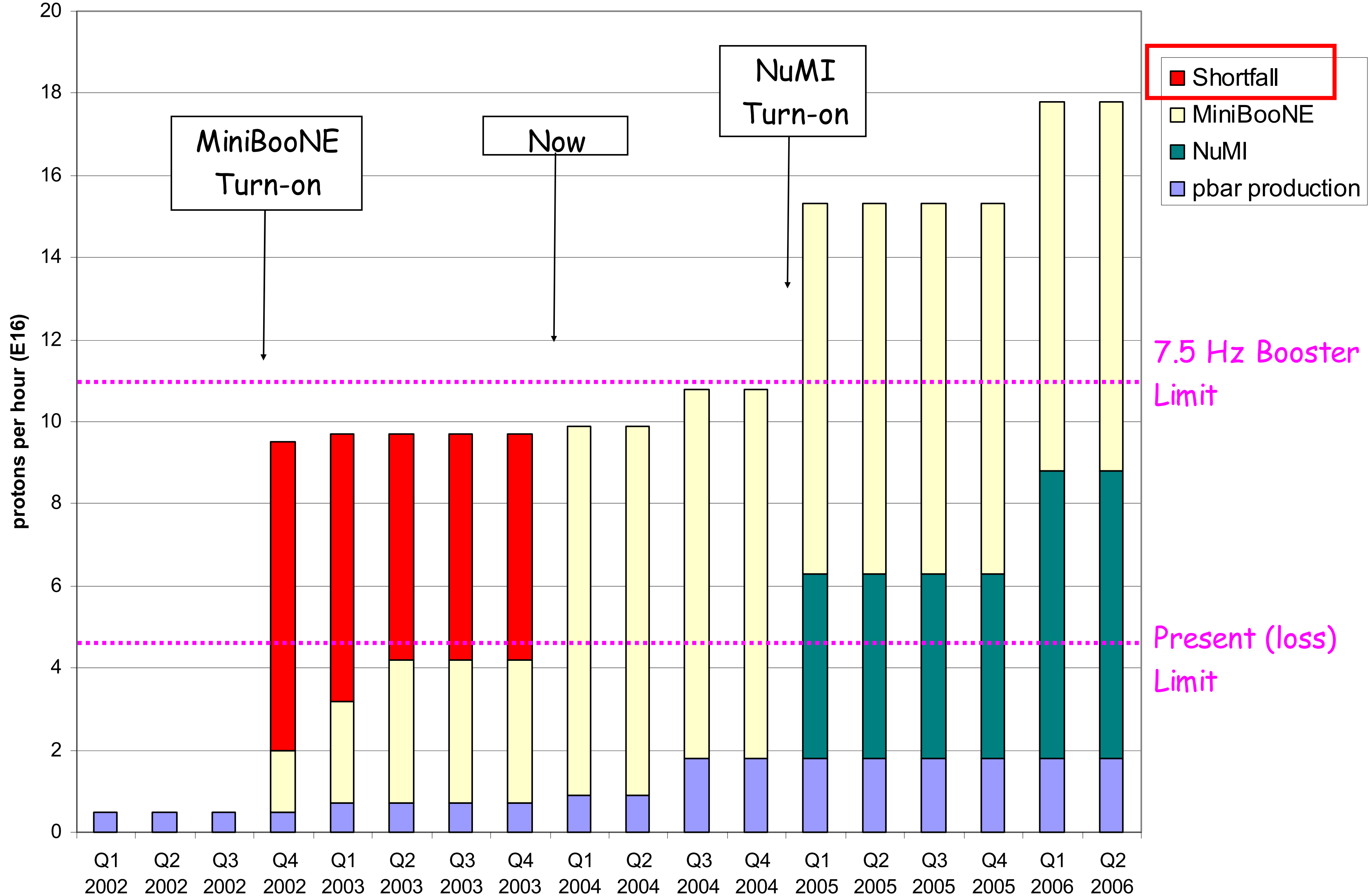
M&D (Shutdown) | Installation | Startup/Commissioning | Run or Data

- Major proton consumers (in order of demand):
  - MiniBooNE
  - NuMI (starting 2005)
  - Pbar production
  - Switchyard 120

Preparing for the Neutrino Program

- Shielding and new radiation assessment
- Vastly improved loss monitoring.
- Numerous hardware improvements
  - e.g new extraction septum and power supply
- New tuning strategies.

Proton Demand



Demand: Summary

- Pbar production
  - current: 0.9E16 p/hr
  - Max (slipstacking): 1.8E16 p/hr
- MiniBooNE
  - current: ~3.5E16 p/hr
  - Request: 9E16 p/hr [5E20 p/yr]
- NuMI
  - Baseline: 4.5E16 p/hr [2-2.5 p/yr]
  - Exotic loading schemes (~2006): ~7E16 p/hr [4E20 p/yr]
  - Occasionally claim: 14E16 p/hr [8E20 p/yr]
- 2005
  - Max pbar + MiniBooNE + baseline NuMI:

~16E16 p/hr (~4 times current limit!)

What MINOS believes they are getting (→ [4E20 p/yr])

Understanding Proton Economics: Proton Timelines

- Everything measured in 15 Hz "clicks"
- Minimum Main Injector Ramp = 22 clicks = 1.4 s
- MiniBoone batches "sneak in" while the MI is ramping.
- Some Booster elements require 2 null prepulses before each 15 Hz batch train.
- Cycle times of interest
  - Min. Stack cycle: 1 inj + 22 MI ramp = 23 clicks = 1.5 s
  - Min. NuMI cycle: 6 inj + 22 MI ramp = 28 clicks = 1.9 s
  - Full "Slipstack" cycle (one, scenario, total 11 batches):

```
   6 inject
+ 2 capture (6 -> 3)
+ 2 inject
+ 2 capture (2 -> 1)
+ 2 inject
+ 2 capture (2 -> 1)
+ 1 inject
+ 22 M.I. Ramp
----------------------
39 clicks = 2.6 s
```

(More protons but longer cycle time)

Proton Scenarios

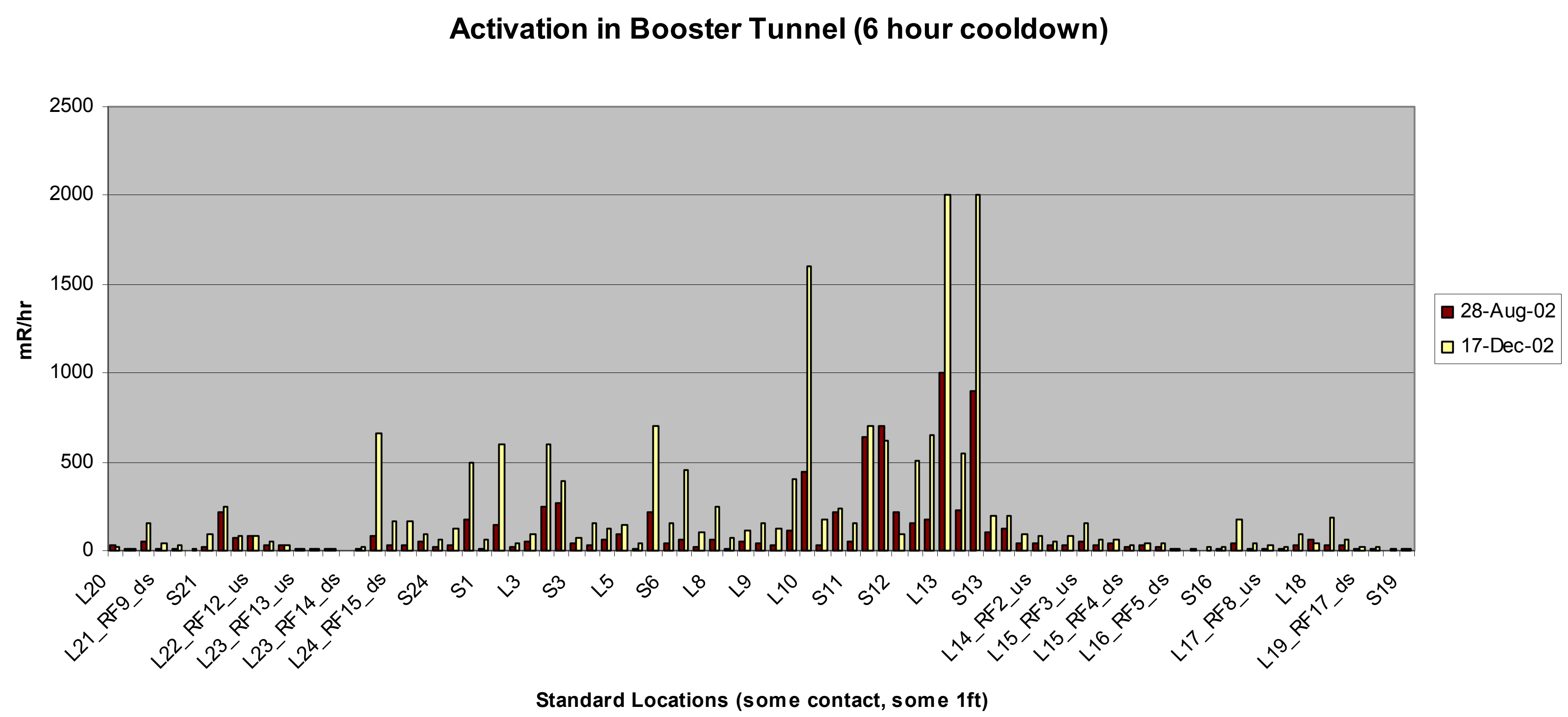
	avg. Booster	protons per year				
Scenario	rate (Hz)	pbar	MiniBooNE	NuMI	total	/present max
pbar	1.5	5.0E+19	0.0E+00	0.0E+00	5.0E+19	20%
pbar+present BooNE (loss limited)	4.0	5.0E+19	2.0E+20	0.0E+00	2.5E+20	100%
pbar+full BooNE	6.5	5.0E+19	5.0E+20	0.0E+00	5.5E+20	220%
slipstacked pbar	2.0	1.0E+20	0.0E+00	0.0E+00	1.0E+20	40%
slipstacked pbar+BooNE	7.0	1.0E+20	5.0E+20	0.0E+00	6.0E+20	240%
slipstacked pbar+5 NuMI batches (NuMI "baseline")	4.4	9.7E+19	0.0E+00	2.4E+20	3.4E+20	135%
slipstacked pbar+9 NuMI batches	5.6	8.6E+19	0.0E+00	3.9E+20	4.7E+20	189%
slipstacked pbar+BooNE+5 NuMI batches	9.5	9.7E+19	5.2E+20	2.4E+20	8.6E+20	342%
slipstacked pbar+BooNE+10 NuMI batches	11.3	8.3E+19	5.4E+20	4.2E+20	1.0E+21	417%

Booster Hardware Issues

Booster Activation Issues

Maximum we can imagine delivering without major Main injector Upgrades

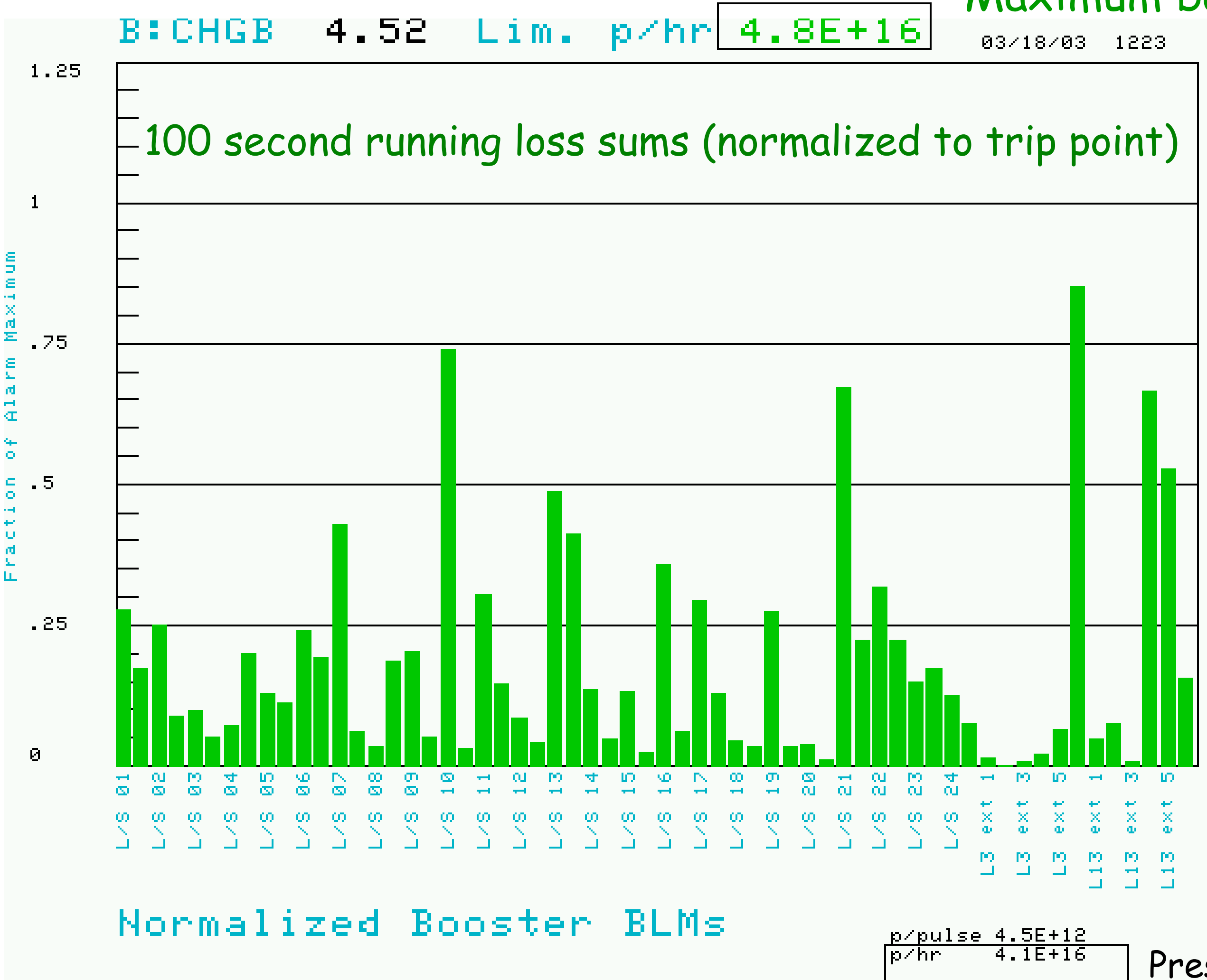
The Bad News: Booster Tunnel Radiation Levels



Any further increase in protons must come without increasing losses.

Operational Issues: Limiting Booster Losses

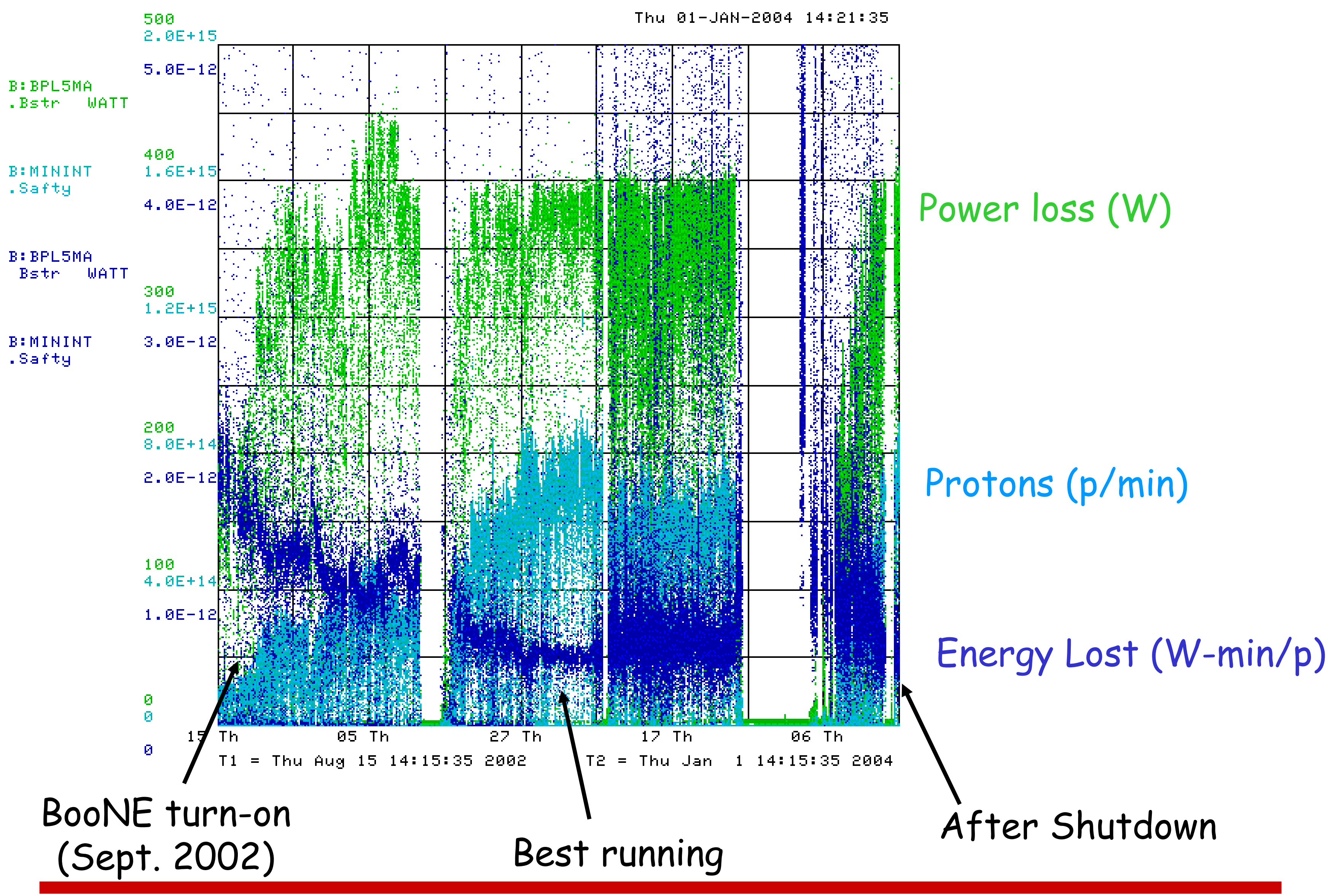
Maximum based on trip point



Present rate

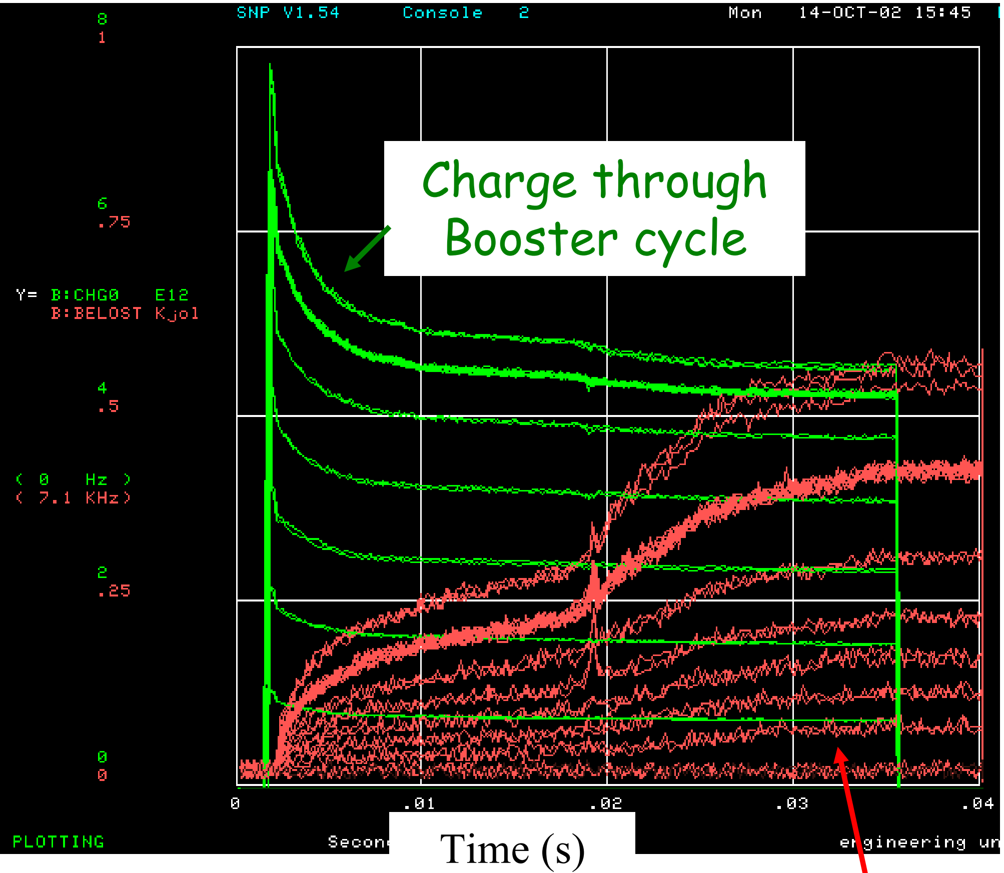
Also limit total booster average power loss (B:BPL5MA) to 400W.

Historic Performance (through last week)



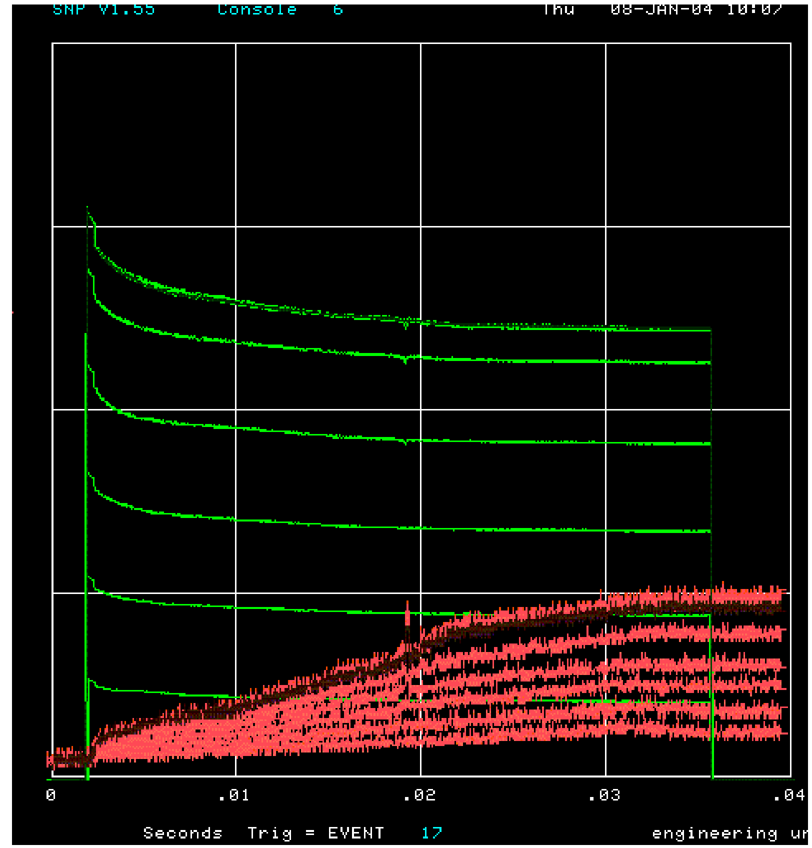
How far have we come?

Before MiniBooNE



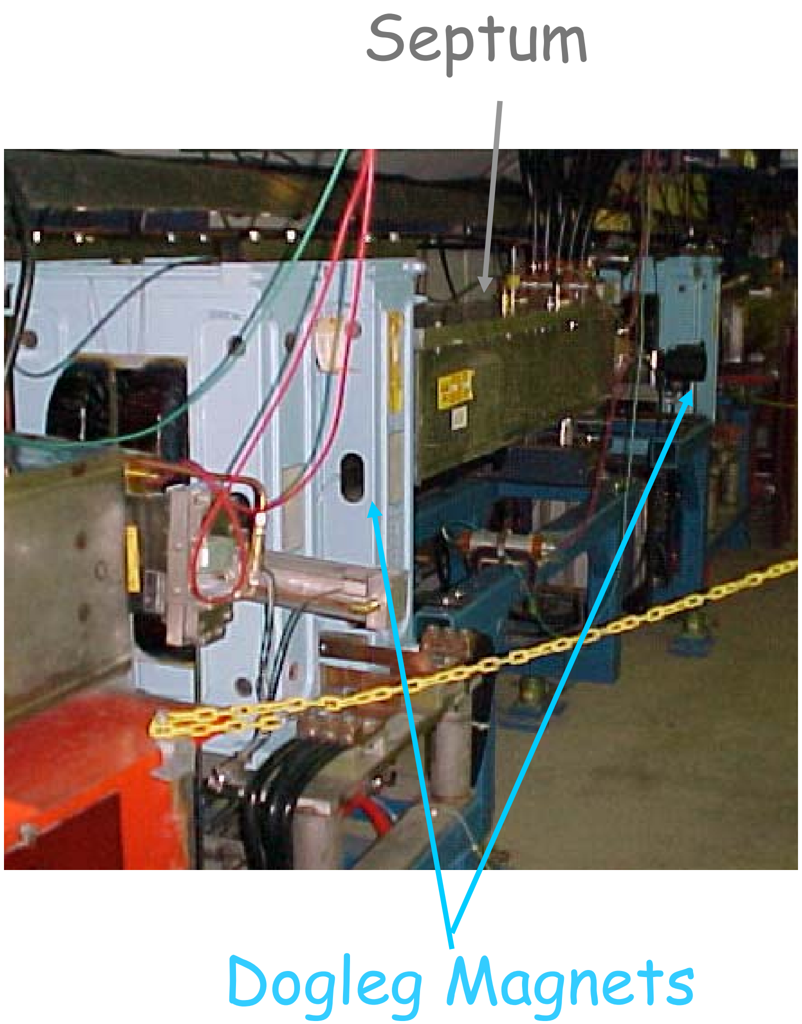
Energy Lost

Now (same scale!!)



Note less pronounced injection and transition losses

Solving Problems: Extraction Doglegs

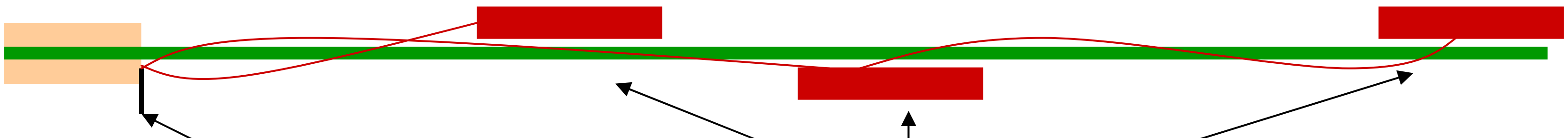


- Each of the two Booster extraction septa has a set of *vertical* dogleg magnets to steer the beam around it during acceleration.
- These magnets have an edge focusing effect which distorts the *horizontal* injection lattice:
  - 50% increase in maximum β
  - 100% increase in maximum dispersion.
  - Harmonic contributions.
- This discovery was a direct result of increased Beam Physic involvement.
- Effect goes like I^2. Now tune to minimize.

- Modified one of the two extraction regions during the recent shutdown to reduce problem (40% total reduction in lattice deviations)
- Will do second next year
- In then end, close to an 80% reduction in distortions

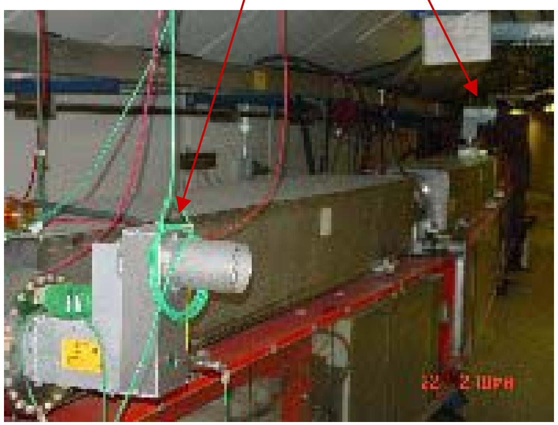
Solving Problems: New Collimator System

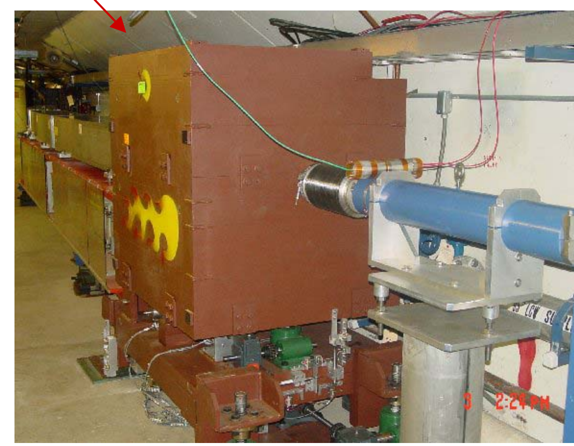
Basic Idea…



A scraping foil deflects the orbit of halo particles…

…and they are absorbed by thick collimators in the next periods.





- Should dramatically reduce uncontrolled losses

Other Major Shutdown Work

- New Linac Lambertson
  - Should improve 400 MeV line optics
  - Simplifies linac tuning
  - Reduce losses
- Four Large aperture Booster extraction magnets (EDWA)
  - Should reduce losses at extraction.
- Complete vertical alignment network of Booster
  - First in ??? Years
  - Will be used to align entire machine
- New power supply for second extraction region
  - Part of overall upgrade project
- Linac water system upgrade
- Booster vacuum system upgrade
- Numerous other jobs

Formulating a Plan

- The lab has recognized that the proton demands of the experimental program are significant, if not daunting, and will require substantial efforts to meet.
- As the financial burden of Run II begins to ease, it's envisioned that financial resources on the order of $20M will be diverted to these efforts over the next few years.
- We are in the process of putting together a plan with the maximum likelihood of reaching these goals.
- Ultimate goal is to generate a project similar to Run II
- However, because the future (MiniBooNE) is already here, such a plan will necessarily have near and long term components.

Near Term Priorities

- Optimizing Booster for improved lattice:
  - Tuning and characterizing 400 MeV line (Linac to Booster).
  - Tuning Booster orbit to minimize losses.
- Commission Collimators:
  - Once we have Booster optimized to the new lattice, we will begin to exercise the collimator system.
  - Estimate about 2 months to bring into standard operation.
- Aperture Improvments:
  - Alignment
    - Complete (magnet) vertical network done over shutdown
    - Will analyze and effect moves when opportunities arise
    - Working on a systematic method for aligning straight sections.
    - Formulating a plan for a complete, modern, network by next summer
  - Orbit control
    - Ramped orbit control program has been written.
    - Will be commissioned soon (new personnel)
    - Important now that collimator is in place.
  - Prototype RF Cavities
    - Two large aperture prototype cavities have been built, thanks to the help of MiniBooNE and NuMI universities.
    - We will install these as soon as they are ready to replace existing cavities which are highly activated.
- It's hoped this work will allow us to reach the MiniBooNE baseline this year.

Issues over the Next Year

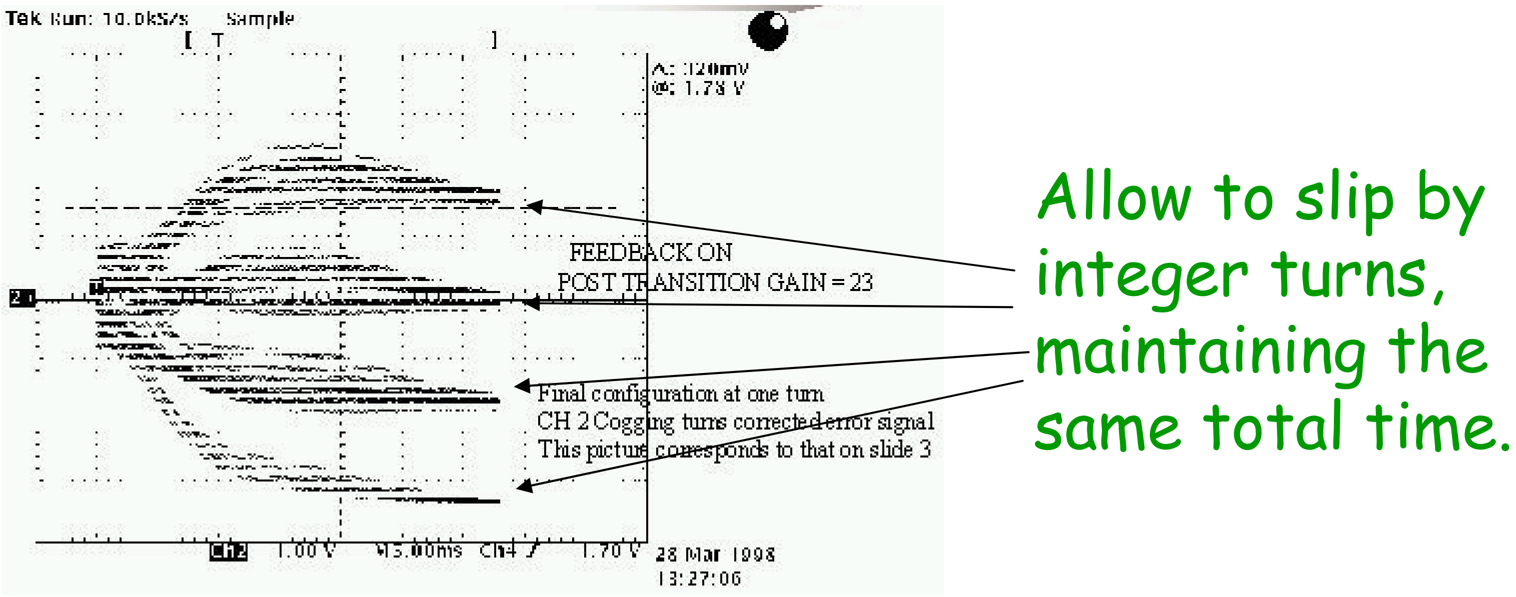
- Linac Characterization and Reliability
  - Increase instrumentation of old linac to study instabilities.
  - Develop set of performance parameters.
- Booster improvements.
  - Prepare for modification of second extraction region
    - New septum
    - Modified dogleg magnets
    - On track for next year's shutdown.
  - Injection Bump (ORBUMP) Power Supply
    - Existing supply a reliability worry.
    - Limited to 7.5 Hz
    - Building new supply, capable of 15 Hz.
    - Aiming for next year's shutdown.
  - Under consideration: New ORBUMP Magnets
    - Existing magnets limited by heating to 7.5 Hz
    - Working on a design for cooled versions.
    - These, with a new power supply, will make the Booster capable of sustained 15 Hz operation.
    - Biggest decision for the near future.

Multibatch Timing

- In order to Reduce radiation, a "notch" is made in the beam early in the booster cycle.
- Currently, the extraction time is based on the counted number of revolutions (RF buckets) of the Booster. This ensures that the notch is in the right place.
- The actual time can vary by > 5 usec!
- This is not a problem if booster sets the timing, but it's incompatible with multi-batch running (e.g. Slipstacking or NuMI)
- We must be able to fix this total time so we can synchronize to the M.I. orbit.
- This is called "beam cogging".

Active cogging

- Detect slippage of notch relative to nominal and adjust radius of beam to compensate.



- Efforts in this area have been recently increased, with the help of a Minos graduate student (R. Zwaska).
- Aim to get working in the next few months

Long Term, Big $$ Ideas Under Consideration

- New Booster RF system:
  - Larger aperture cavities (two prototypes will be installed soon).
  - New solid state preamps and modulators (would pay for itself in a few years).
- New Linac front end:
  - Replace Preac and 200 MHz linac with RFQ feeding 400 MHz klystron-driven linac.
  - Addresses 7835 Amplifier Tube Problem
  - Possible part of proton driver?
- Reduce Main Injector ramp time:
  - Still needs time to load protons
  - Needs to fit in with stacking.
  - Necessary to get the kind of protons that off-axis is talking about.

Longevity Issues

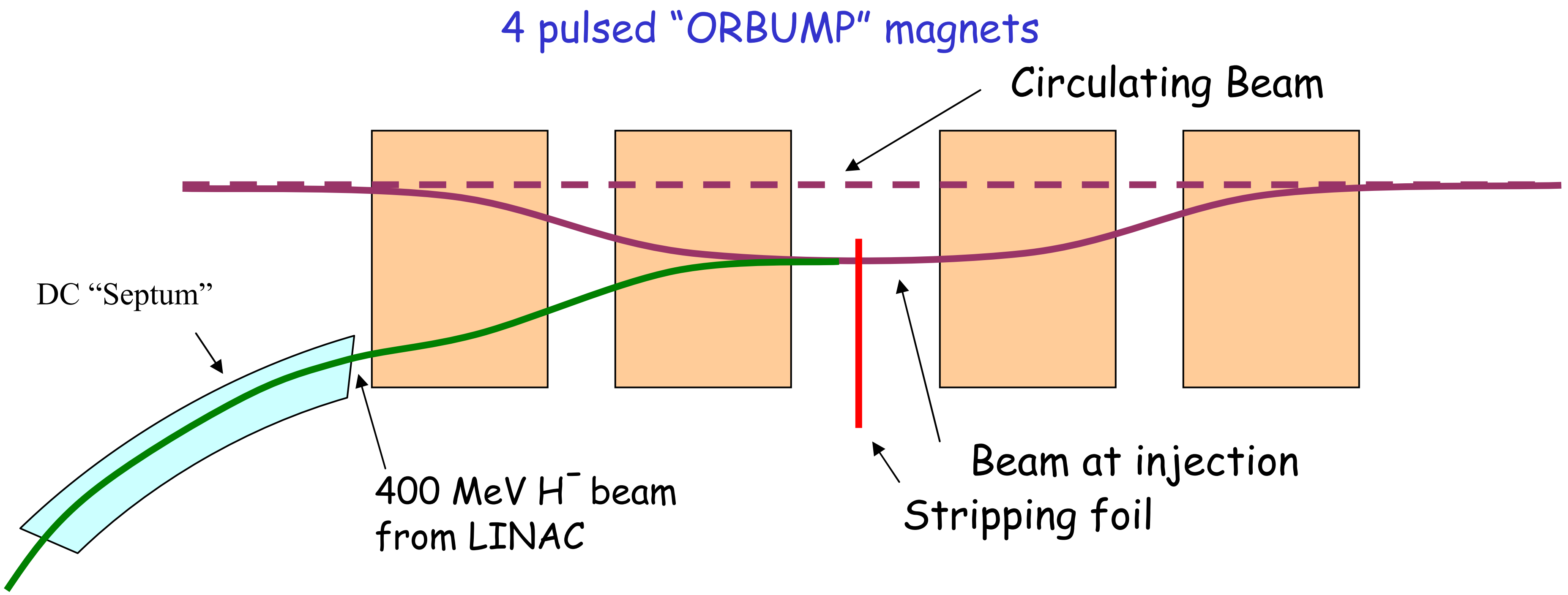
- Linac
  - 200 MHz Power Amplifier tubes
    - 5 sockets. Replace about 3/year
    - One vendor, in danger of going out of business
    - Quality control problems
    - Currently 3 spares (most in several years)
    - No drop-in replacement
  - 800 MHz klystrons
    - 7 sockets
    - Installed in 1992
    - One failure in 1997 -> replaced, no problem
    - One failure in early December -> replaced, no problem
    - One faiulre at Christmas -> THREE BAD SPARES
    - Now we're a bit worried!
- Booster
  - Old, but will probably last with care.

Summary

- We have a good understanding of the proton demands over the next few years in the context of the limitations of the Fermilab accelerator complex.
- We have made remarkable progress toward meeting these demands, but are still falling well short.
- We are pursuing an ambitious plan to attempt to meet these demands, but cannot yet guarantee its success.
- The next few months will be very important.

Extra Slides for Questions

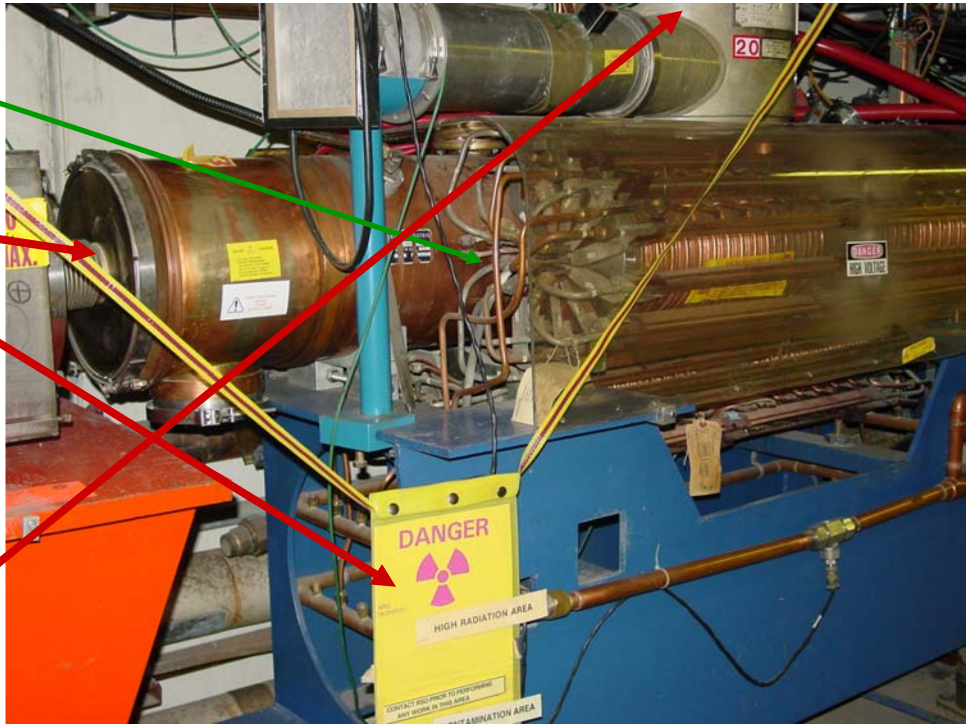
Multi-turn Ion Injection



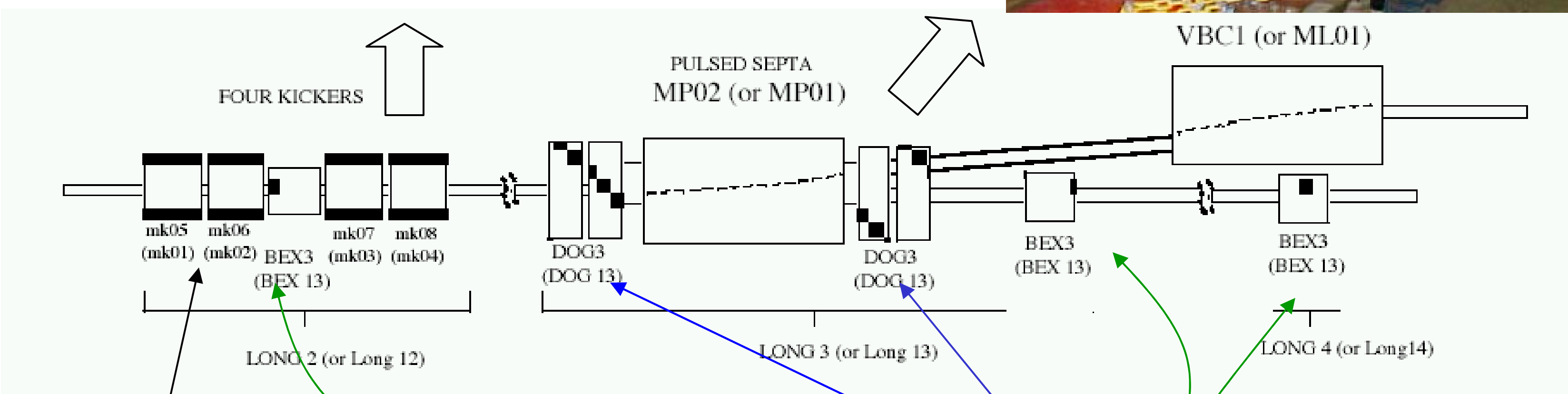
- At injection, the 40 mA Linac H- beam is injected into the Booster over several "turns" (1 turn ~5E11).
- The orbit is "bumped" out, so that both the injected beam and the circulating beam pass through a stripping foil, after which they circulate together.
- At the moment, heating in the ORBUMP and power supply magnets limit our average rep rate (including prepulses to ~7.5 Hz).

Booster RF System

- 18 more or less original RF cavities and power supplies.
- tunable from 38 to 53 MHz during acceleration.
- 2 $\frac{1}{4}$" drift tube one of our primary aperture restrictions; new design being considered.
- Existing cavities might overheat at >7.5Hz. Need to re-commission cooling
- In-tunnel Power Amplifiers (PA's) are by far the highest maintenance item in the Booster



Booster Extraction (Two Extraction Regions)

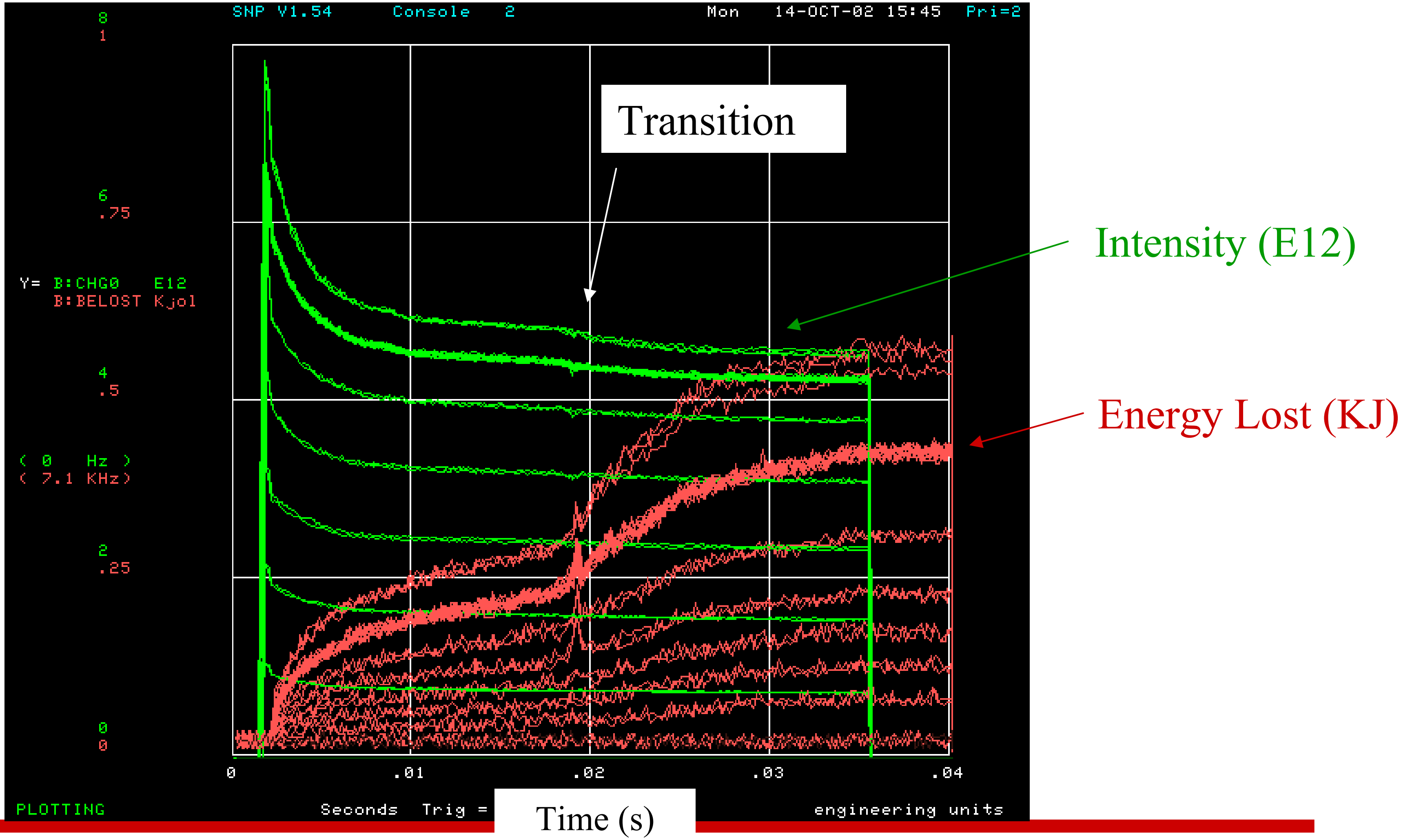


Fast (~40 ns) kickers

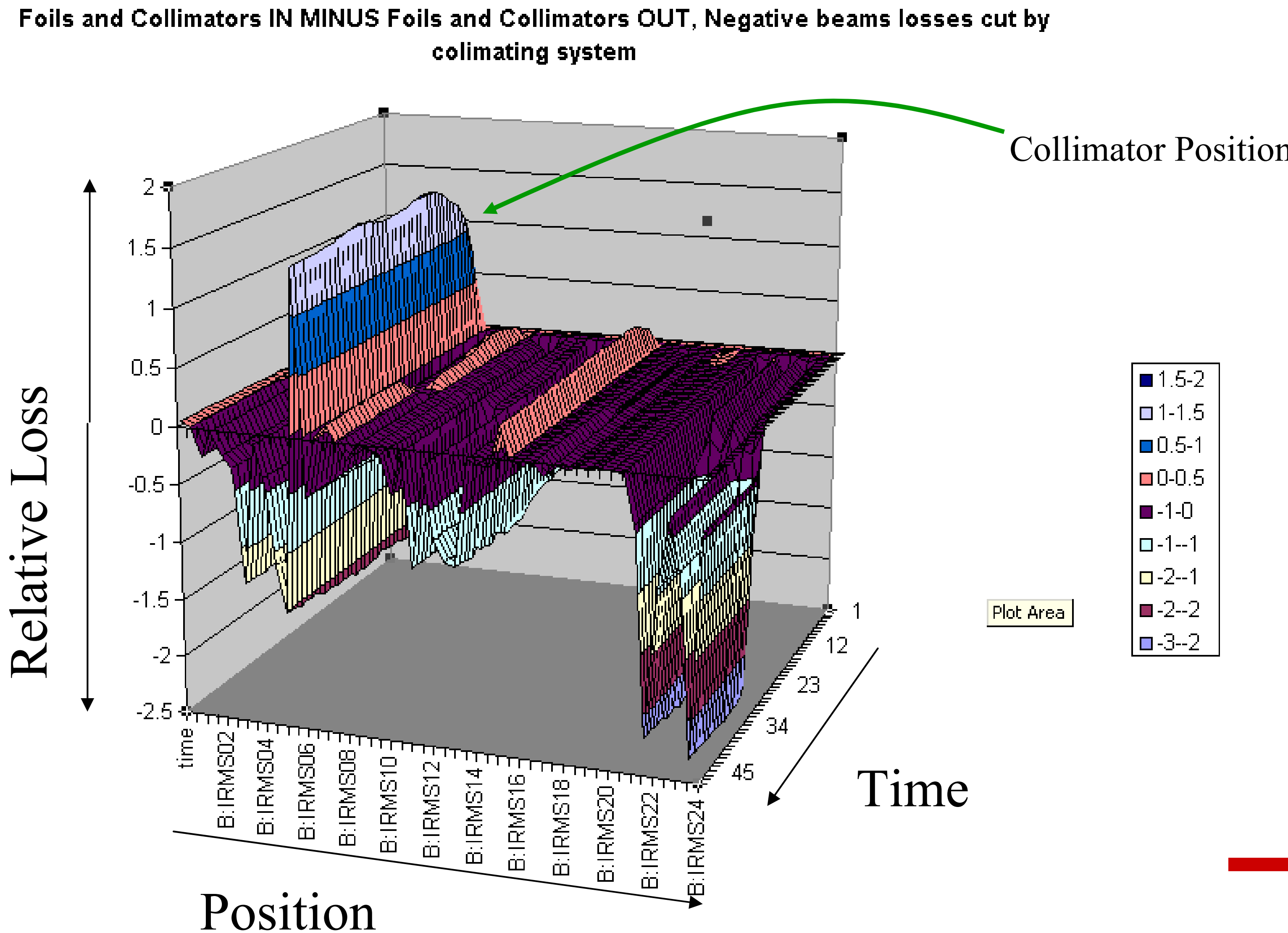
DC "doglegs" work with ramped 3-bump (BEXBUMP) to maintain 40π aperture below septum

Typical Booster Cycle

Various Injected Intensities



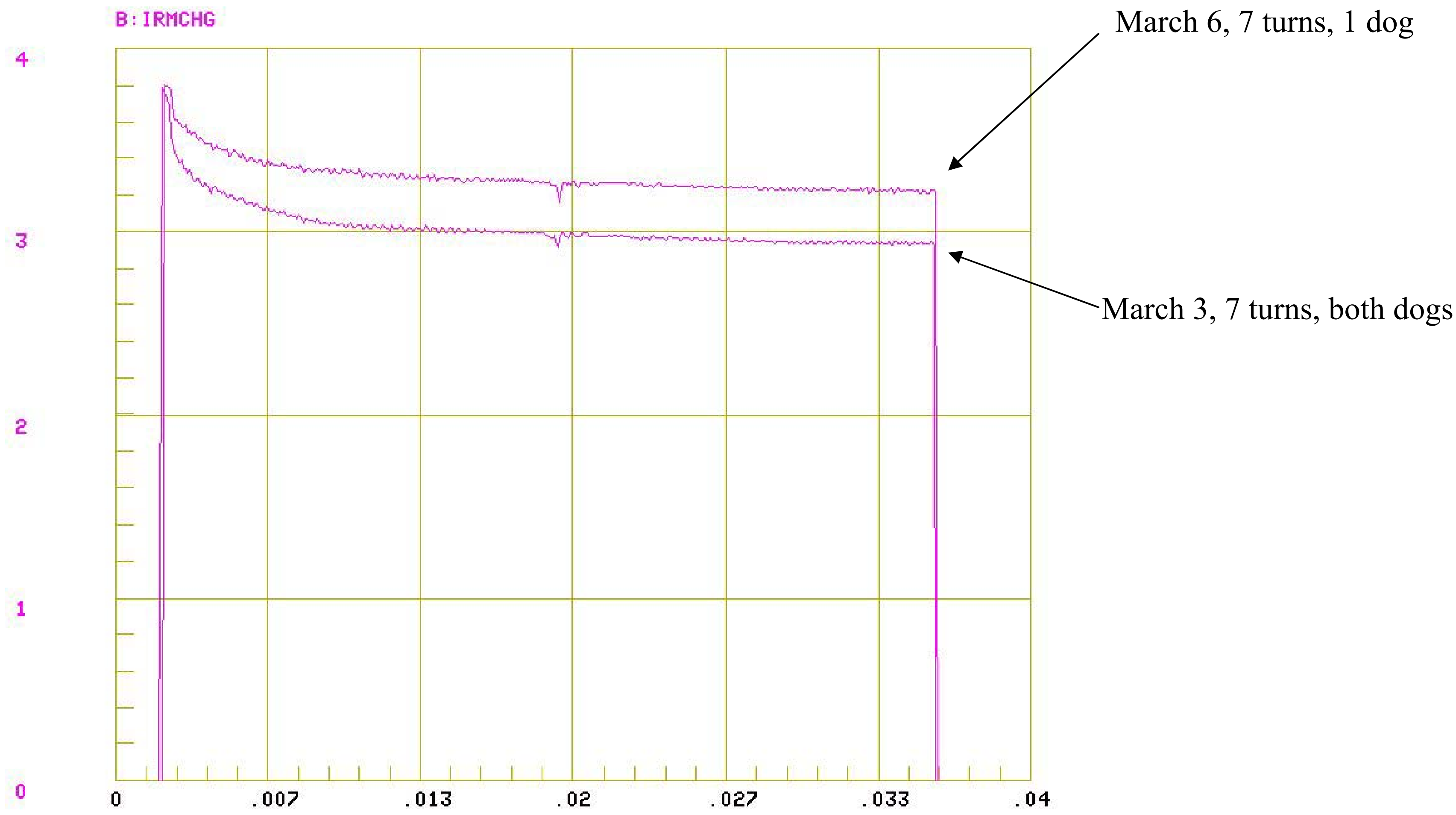
Differential Loss Monitor Example: Collimators in – Collimators Out



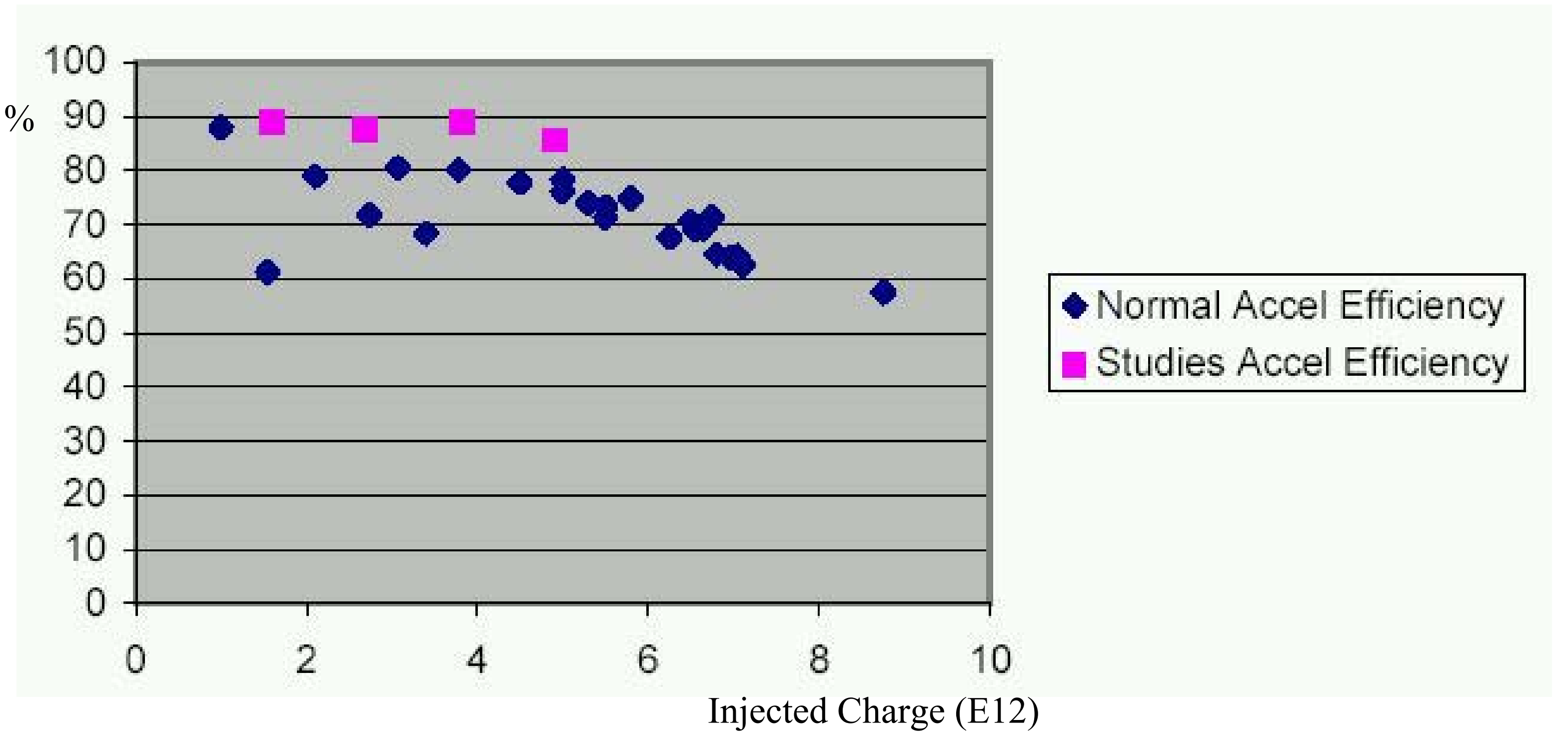
Dead Dog Studies

- Took advantage of recent TeV Magnet failure to raise the Long 13 (dump) septum and turn off the associated dogleg.
- Doglegs almost exactly add, so this should reduce the effect by almost half.
- The mode of operation prevents short batching, booster study cycles and RDF operation.
- Had about 36 hours of study in this mode.
- Bottom Line: **major improvement**.

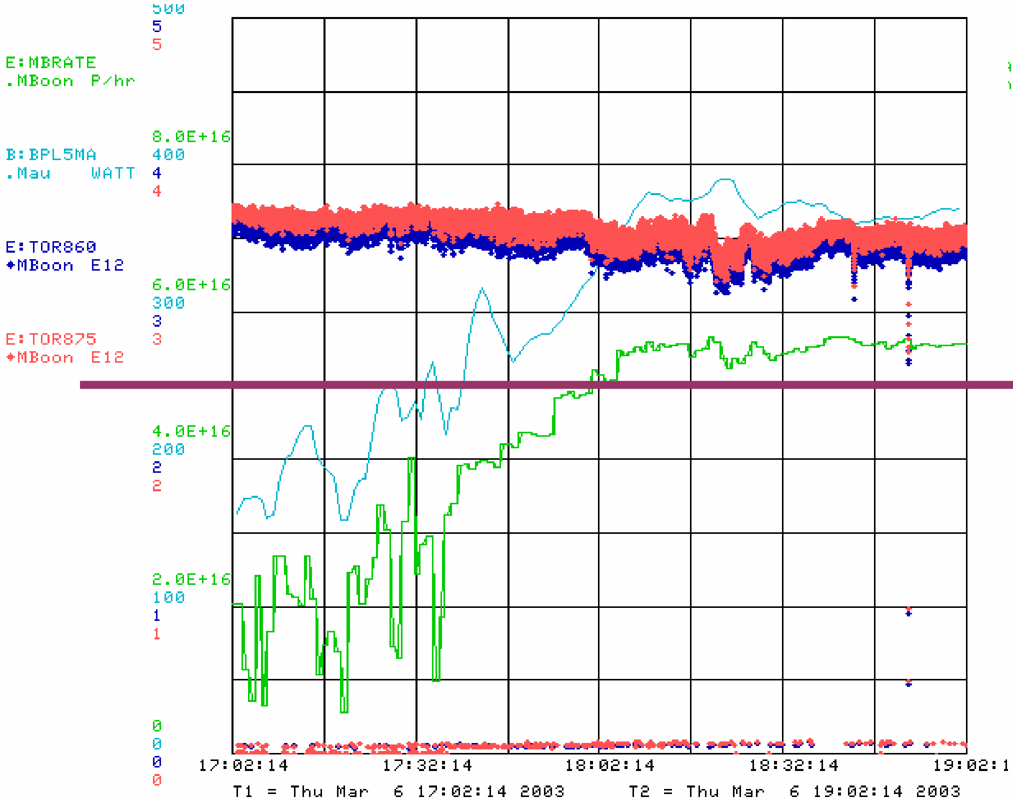
Transmission After Tuning

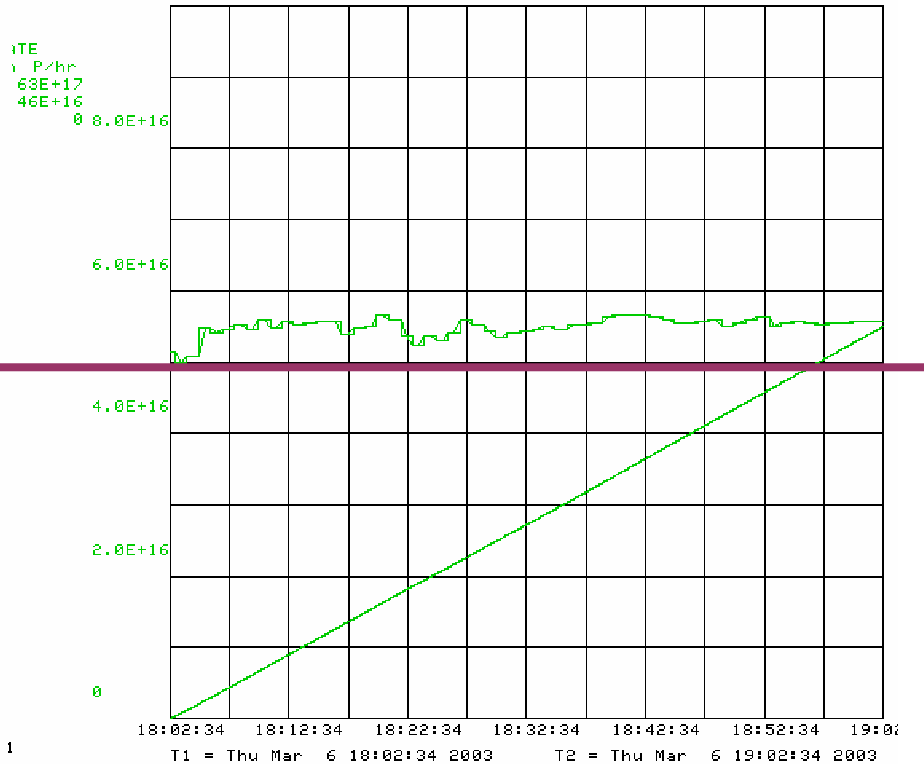


Transmission with One Dogleg



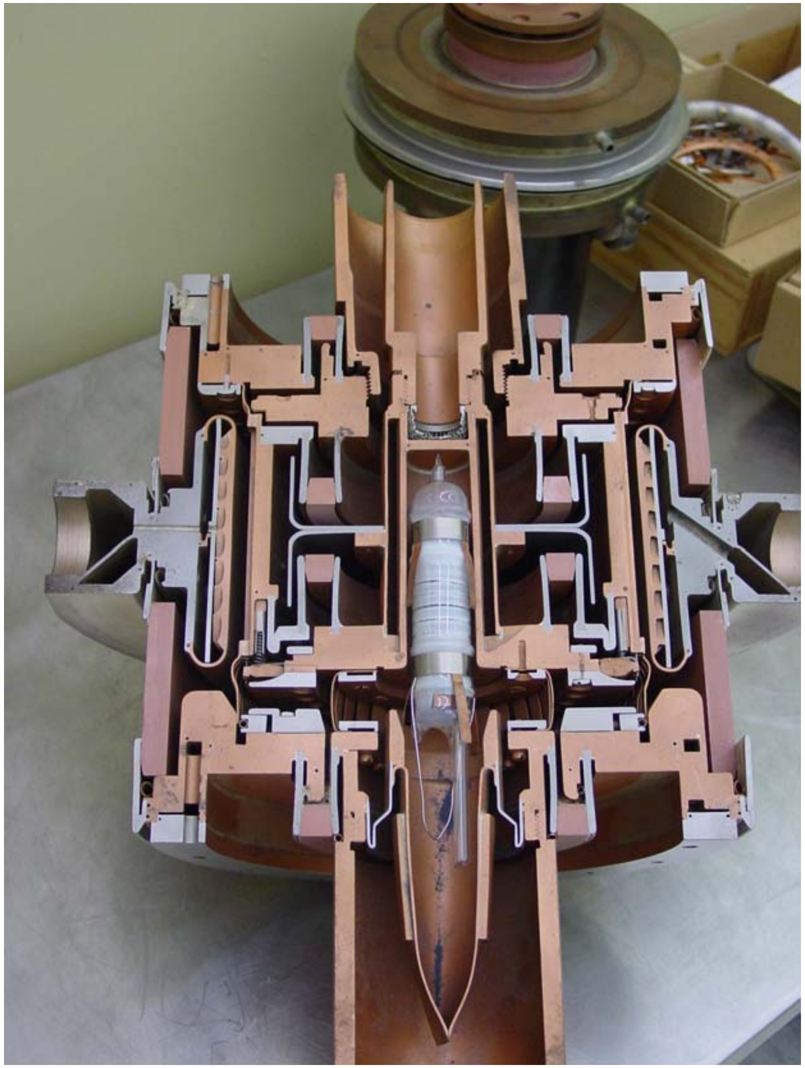
Record Running w/o Dogleg





The 7835 Power Triode – Our BIG Worry

- Very complex technology
  - RF, material science, vacuum, chemistry
- Similar to other tubes made by Burle
  - 4616 & 4617
- 7835 only used in the scientific community.
  - One military user for 4617
- Quality varies from decade to decade



Tube Throughput with Burle

- Median lifetime: 16 months
  - Recent lifetime: Less! (possibly related to vacuum problems)
- We need about 3.41 tubes/year to maintain
  - Assuming historical median
  - With present tubes: twice that.
- Burle now can make/rebuild ~20/year
  - Critical path: Final bakeout; two stands, 3-5 weeks bakeout
  - Also of concern: Supplier delivery time (e.g., ceramics, cathode)
  - Recently had four failures for one success!!
- Delivery time: ~8 months,
  - But, often 12 months!
- This is obviously a worry.

Present 7835 Power Tube Situation

- We've received 5 tubes since the last review
  - Only two delivered from Burle, after numerous failures
  - Two borrowed from BNL
  - One borrowed from Argonne
  - We now have one spare; we have frequently had zero; we have never had two.
  - Next one due "in August".

Hours on the Linac 7835 Power Amplifiers

Station	Tube S/N	Gradient	Filament A	Hours	*Days*	Fraction of median* life	Prob of failure this week
1	N14R6	0.99	6708	13349	*556*	0.84	0.021
2	A1R8	1	6722	4434	*184*	0.41	0
3	N49R6_BNL	0.99	6592	1803	*75*	0.16	0
4	A27R6	0.98	6543	2257	*94*	0.2	0
5	N27R7_BNL	1	6714	1081	*45*	0.1	0
7	BK1	-0.02	184	31	*1*	0	-

*Median lifetime for tubes is about 10750 hours (15750 for tank 1). This is 447 days (656 for tank 1).